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Large-scale Structure and Dynamics of the Most X-ray Luminous Galaxy Cluster Known — RX J1347-1145

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ABSTRACT

We present photometric, spectroscopic and weak lensing analysis of the large-scale structure and dynamics of the most X-ray luminous galaxy cluster known, RX J1347-1145, at $z = 0.451$. We spectroscopically confirmed 47 new members with LDSS3 on the Magellan telescope. Together with previously known members, we measure a new velocity dispersion of $1163 \pm 97 \text{ km s}^{-1}$. The mass inferred from our velocity dispersion is $M_{200} = 1.16^{+0.32}_{-0.27} \times 10^{15} M_{\odot}$, with $r_{200} = 1.85 \text{ Mpc}$, under the assumption of a singular isothermal sphere. We also present a weak lensing analysis using deep CFHT data on this cluster, and find a deprojected mass of $1.47^{+0.46}_{-0.43} \times 10^{15} M_{\odot}$ within r_{200} , in excellent agreement with our dynamical estimate. Thus, our new dynamical mass estimate is consistent with that from weak lensing and X-ray studies in the literature, resolving a previously claimed discrepancy. We photometrically detect and spectroscopically confirm another massive cluster with $\sigma = 780 \pm 100 \text{ km s}^{-1}$ and $M_{200} = 3.4^{+1.4}_{-1.1} \times 10^{14} M_{\odot} \sim 7 \text{ Mpc}$ south-west of RX J1347-1145, which we refer to as RXJ1347-SW. Our spectroscopic survey reveals a possible excess of galaxies in velocity space in the region between RX J1347-1145 and RXJ1347-SW; comparing with simulations, this excess appears consistent with that expected from a large filamentary structure traced by galaxies connecting these two clusters.

Key words: Galaxies: Clusters: General, Galaxies: Clusters: Individual (RX J1347-1145)

1 INTRODUCTION

How galaxy properties are affected by the environment they reside in remains one of the unsolved puzzles of galaxy formation. The galaxy population in clusters has been observed to have different properties from that in the field (e.g. Balogh et al. 2004; Weinmann et al. 2006; McGee et al. 2008), suggesting that this growth of large scale structure is accompanied by a transformation in galaxy properties. However, it is still an open question as to exactly what mechanisms are responsible for this difference (e.g. Balogh et al. 1999; Tanaka et al. 2006).

Clues might come from the outskirt regions of clusters, because that is where field and groups of galaxies are accreting onto clusters, especially along filamentary structures that are seen in simulations (e.g. Bond et al. 1996; Colberg et al. 1999). Groups in the outskirts are particularly

interesting; a recent study by McGee et al. (2009), using a semi-analytic model, shows that a large fraction of galaxies that accrete onto clusters are in groups (but see Berrier et al. 2009), and they might have been pre-processed in the group environment before they fall into clusters (Balogh et al. 2000; Fujita 2004; Li et al. 2009; Balogh & McGee 2009). However, these groups are likely to be different from isolated groups in the field, due to their earlier formation time (Maulbetsch et al. 2007) and the tidal fields from the large-scale structure around clusters (Gnedin 2003). Therefore, closer examination of groups and filamentary structures in the outskirts of clusters, and a comparison with isolated groups in the field, may provide important clues to how the cluster environment affects the properties of galaxies.

We have started an extensive spectroscopic campaign on two contrasting clusters at intermediate redshift, focusing on groups in the outskirt regions out to $\sim 8 \text{ Mpc}$. The

ultimate goal is to put strong constraints on the effect of the environments by comparing properties of groups in the infall regions with those of isolated groups, and with galaxy formation models. In this work, as the first paper of a series, we present results from a pilot study on the dynamics and large-scale structure of one of the clusters, RX J1347-1145 ($z=0.451$).

RX J1347-1145 is the most X-ray luminous cluster in the ROSAT All-Sky Survey (RASS, Schindler et al. 1995), and has been the subject of intense study, through spectroscopic (Cohen & Kneib 2002), X-ray (Schindler et al. 1997; Allen et al. 2002, 2008; Ettori et al. 2004; Gitti & Schindler 2004; Gitti et al. 2007; Bradač et al. 2008; Ota et al. 2008; Miranda et al. 2008), lensing (Fischer & Tyson 1997; Sahu et al. 1998; Kling et al. 2005; Bradač et al. 2005, 2008; Halkola et al. 2008; Miranda et al. 2008; Broadhurst et al. 2008), and Sunyaev-Zel'dovich (SZ) effect (Pointecouteau et al. 2001; Komatsu et al. 2001; Kitayama et al. 2004) analyses. The centre of the cluster was initially thought to be dynamically relaxed. Although there are two very bright galaxies near the centre (usually referred to as the brightest cluster galaxy (BCG) and the second BCG), they are only 18 arcsec (~ 0.1 Mpc) apart in the plane of sky, and < 100 km/s in velocity. However, a discrepancy between the relatively low mass measured dynamically by Cohen & Kneib (2002), compared with X-ray and weak lensing measurements, led to the suggestion that the cluster is actually undergoing a major merger. This hypothesis has received support recently from the discovery of shocked gas in the centre of the cluster (Allen et al. 2002; Gitti & Schindler 2004; Ota et al. 2008; Bradač et al. 2008; Miranda et al. 2008; Komatsu et al. 2001).

Most of the previous work is on the central region of the cluster; in this paper, we focus on the dynamics and the large-scale structure of this cluster, using imaging data obtained with CFHT and spectroscopic data obtained with the Magellan telescope. We describe the data in §2. In §3, we present the photometric and spectroscopic analysis on the large-scale structure, and the detection of another massive cluster, RXJ1347-SW, ~ 7 Mpc from the cluster centre. We also present mass estimates of the two clusters through dynamical methods and weak lensing analysis. In §4 we compare our mass estimates of the main cluster with those in the literature, and discuss the possible filamentary connection between the main cluster and RXJ1347-SW using simulations. Our findings are summarized in §5.

Throughout this paper, we assume a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$. All magnitudes are in the AB system.

2 DATA

2.1 Imaging

Deep g' , r' , i' , z' band images of the cluster over a 1 square degree field were obtained using Megaprime on the CFHT in semester 05A (proposals 05AC10 and 05AC12), with total exposure times of 4200 s in g' , 7200 s in r' , 1600 s in i' , and 3150 s in z' . The z' band data will not be mentioned further, because they are not relevant for the work presented here. In each filter, images from single exposures are co-added using

SWARP v2.16.0 (Bertin et al. 2002) and photometry is performed using SExtractor v2.4.4 (Bertin & Arnouts 1996), with the camera run zero point. The latter quantity is provided by Elixir, and is extracted from the Landolt field observed under photometric conditions every night. Since our science data were not taken under photometric conditions, a zero point offset calculated from a short exposure taken under photometric conditions is applied. The typical seeing is $\sim 0.8''$, $\sim 0.7''$ and $\sim 1''$ in g' , r' and i' band respectively. Colours are measured using magnitudes within a fixed aperture of diameter 4.7 arcsec, which is much larger than the seeing difference in different filters. The magnitude measured within the Kron radius (*mag_auto*) is considered as the total magnitude for each object. Although crowding and blending of objects affects the photometry for about ten percent of the galaxies in our sample, we have checked that none of the results presented here are sensitive to this.

Star-galaxy separation is based on the stellar locus defined by the half-light radius as a function of total magnitude, in combination with the SExtractor parameter, *class_star*. Objects with *class_star* ≤ 0.98 in the g' band, and not on the stellar locus, are considered galaxies. The completeness limit for galaxies is ~ 0.8 mag brighter than the 5σ limit for point sources (Yee 1991); therefore, the completeness limit for galaxies in our catalog in the three bands that are relevant in this work is estimated to be $g' \sim 25$ mag, $r' \sim 25$ mag, and $i' \sim 23.2$ mag.

2.2 Spectroscopy

2.2.1 Observations

In this section, we first describe our spectroscopic observation at the four pointings (shown in Figure 1) that are chosen based on the large-scale structure traced by red-sequence galaxies, which will be described in §3.1.

To make the survey more efficient, we use the combination of $(g' - r')$ and $(r' - i')$ colour information to eliminate obvious higher redshift galaxies (see figure 6 in Lu et al. 2009 for more details). Moreover, we select galaxies with $i' \leq 22$ mag. This ensures that for objects of interest here ($(g' - i') < 3$) our sample is complete in each band, and the colour measurement is reliable. We make sure our targets are not colour biased; as can be seen in Appendix A, the completeness in each pointing for the red and blue populations separately is similar, at ~ 50 per cent.

Spectra were obtained using the Low Dispersion Survey Spectrograph 3 (LDSS3) on the 6.5 meter Clay Telescope over the nights from 2008 April 28th to May 1st. The pointing positions are indicated in Figure 1, each with a FOV of 8.3 arcmin in diameter (corresponding to $r=1.4$ Mpc at the redshift of the cluster). The VR filter and Medium Red grism were used, which covers the wavelength range 5000Å to 7200Å. At the redshift of the cluster, the important spectral features CaH, CaK, G-band, H δ and [OII] fall into this wavelength range. Each pointing was observed with two masks, with an average of ~ 60 objects and 3x20 mins exposure, per mask, with slit width 1.2 arcsec, providing a spectral resolution of ~ 14 Å.

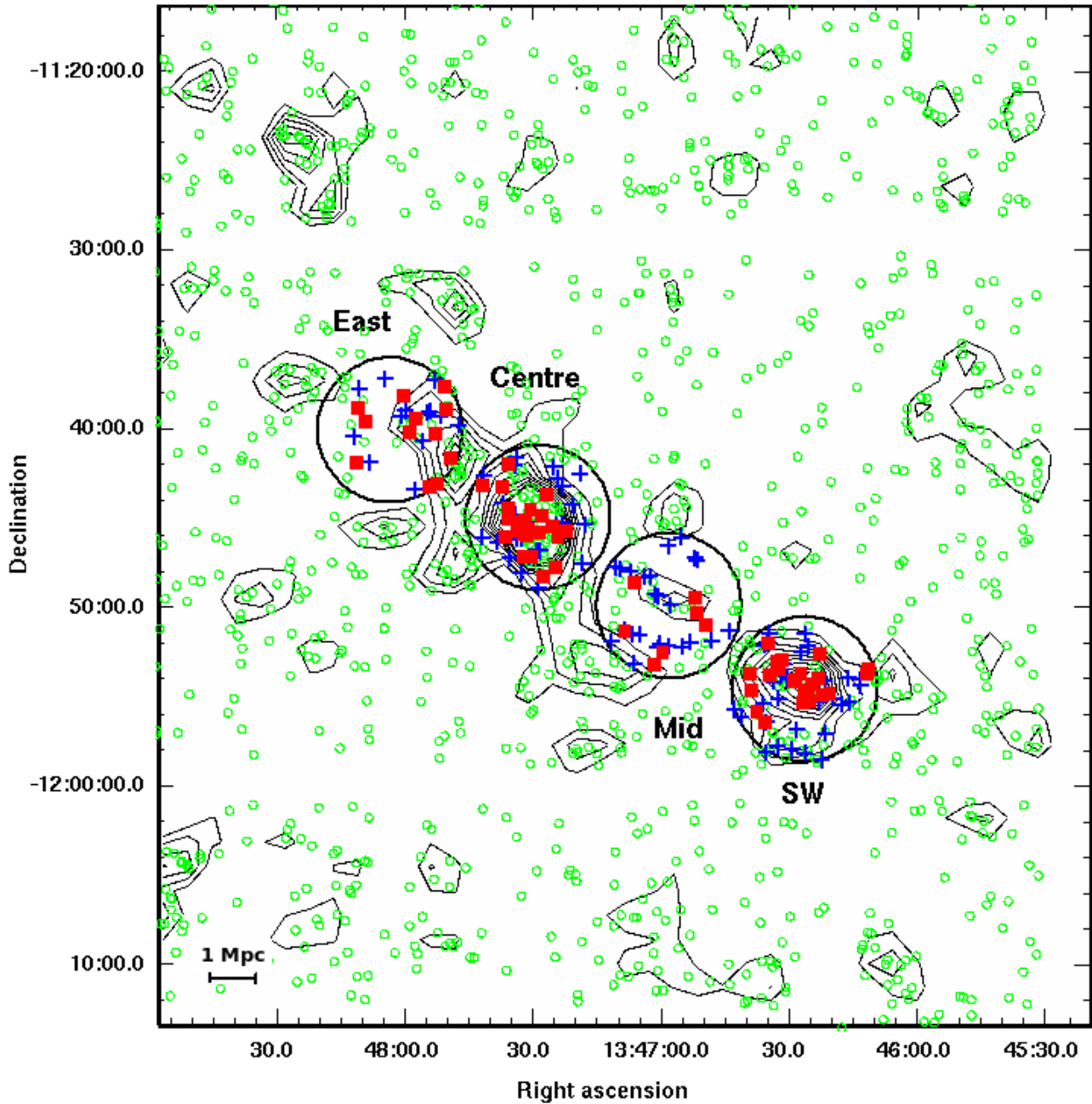


Figure 1. The spatial distribution of the large-scale structure with the surface density contours of red galaxies overlaid. The density contours start at 2σ from the mean and increase with an interval of 1σ . The small circles indicate all galaxies with red colours, the squares and crosses are respectively confirmed red and blue galaxies that are associated with the large-scale structure. The four large circles indicate the pointing positions with spectroscopic follow-up.

2.2.2 Data Reduction

The 2d raw spectra were first reduced using the COSMOS2 software package, then 1d spectra were extracted and redshifts were determined using a modified version of *zspec* kindly provided by Renbin Yan (Cooper et al. 2009). In *zspec*, spectra are first compared with eigen-templates and the ten best-fitted redshifts are provided. We then visually

examine the spectra and determine the best redshift. Usually the first or second choice provided is a good fit. Occasionally when none of the ten choices is a good match, we manually cross-correlate the spectral features and find the best-fit redshift. We consider redshifts determined from at least three supporting spectral features as secure. Two ex-

ample spectra, near the magnitude limit of our survey, are shown in Appendix C.

For the 473 objects targeted, we obtained 400 secure redshifts, which are used in the analysis here. Further details on the success rate, and the efficiency of our survey are presented in Appendix A. From the objects that have duplicate observations, the uncertainty on the redshift is estimated to be $\sim 113 \text{ km s}^{-1}$ in the rest frame (see Appendix B). We also compare the redshift of the common objects in our catalogue with that from Cohen & Kneib (2002), and find no systematic difference between these measurements (Appendix B); therefore, in the following analysis, we add the extra 34 redshifts from Cohen & Kneib (2002) to our sample when applicable.

3 RESULTS

3.1 Photometrically Identified Large-Scale Structure

In this section, we describe the large-scale structure traced by the red-sequence galaxies. Again, only galaxies with $i' \leq 22$ mag are used, for reasons discussed in §2.2.1. At the redshift of this cluster ($z = 0.45$), the $(g' - i')$ colour brackets the 4000\AA break; therefore we use this colour to identify red-sequence galaxies around this cluster, using a method based on the Red-sequence Cluster Survey technique (e.g. Gladders & Yee 2000; Lu et al. 2009). We define the red-sequence at the redshift of the cluster using known cluster members from Cohen & Kneib (2002) that have $(g' - i')$ colour measurement in our catalogue. Given the small slope and the scatter of the colour, we choose to use a red-sequence that has zero slope with a half width of 0.15 mag. Assuming the probability distribution of the colour of each galaxy is Gaussian, with σ being the error on the colour measured from SExtractor, we can calculate the probability of each galaxy belonging to the colour slice (for details see Gladders & Yee 2000). The fact that the colour error from SExtractor is likely to be underestimated is not important here, because the width of the colour slice used is much wider than the colour uncertainties. We consider galaxies with at least 10 per cent probability as red-sequence galaxies, and they are plotted as small circles in Figure 1. Our results here are insensitive to the details of how the red-sequence galaxies are selected.

Using the background number counts measured from the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) Wide field 1, we can calculate the overdensity of red-sequence galaxies. We define the significance of the overdensity as the background-subtracted number of red-sequence galaxies divided by the r.m.s. of the background distribution. The contours of the significance map, smoothed over a region of radius ~ 0.5 Mpc with a top hat function, are plotted in Figure 1, starting from 2σ , with an interval of 1σ .

The most significant peak ($\sim 25\sigma$) is the main cluster (the pointing “Centre”). The number of red-sequence galaxies (background subtracted) within 0.5 Mpc from the cluster centre, brighter than $m^* + 2$ ($i' = 22$ mag), denoted N_{red, m^*+2} , is $\sim 46 \pm 7$, where the uncertainty is estimated using Poisson statistics. Converting N_{red, m^*+2} to N_{200} ac-

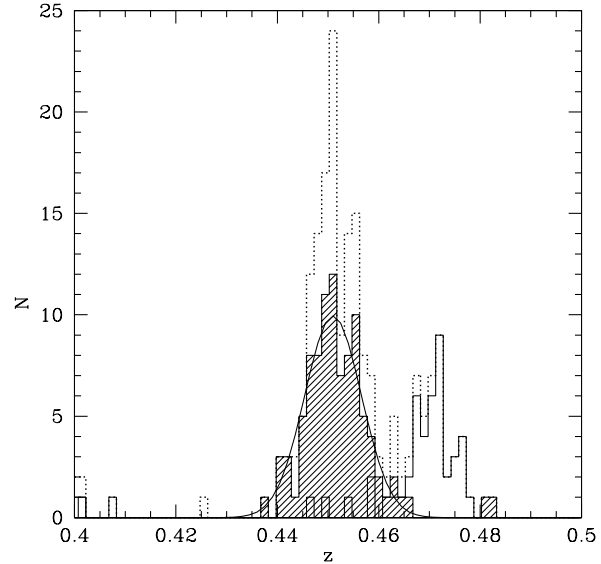


Figure 2. The galaxy redshift distribution from the full area is shown as the dotted, open histogram. The shaded histogram shows the distribution of galaxies in the centre of the main cluster ($r \lesssim 1.4$ Mpc), with a Gaussian function that is statistically consistent with this distribution, overlaid. The redshift distribution of galaxies within $r \lesssim 1.4$ Mpc around RXJ1347-SW is shown as the solid open histogram.

cording to figure 8 in Lu et al. (2009), and using the scaling relation between N_{200} and M_{200} (Johnston et al. 2007; Hansen et al. 2007), we estimate the mass of the main cluster from its richness to be $M_{200} \sim 1.4^{+0.4}_{-0.3} \times 10^{15} M_{\odot}$; although we note the conversion from N_{red, m^*+2} to N_{200} for such a high richness system is extrapolated from lower richness systems.

There is another prominent peak with a significance of $\sim 10\sigma$, about 7 Mpc (projected) away from the main cluster (pointing “SW”). The N_{red, m^*+2} for this system is $\sim 22 \pm 5$, which corresponds to $M_{200} = (3.3^{+1.3}_{-1.6}) \times 10^{14} M_{\odot}$. This suggests this system is a cluster in its own right, and we will refer it as RXJ1347-SW.

The significance contours also reveal several clumps of overdensities in the infall region around the main cluster, and an elongated large-scale structure running from NE to SW, along a line connecting the main cluster and RXJ1347-SW. Four positions along this line are targeted for our spectroscopic follow-up with the Magellan telescope as described in §2.2.1. (Note the significant overdensity east of the pointing “Mid” has been targeted with our on-going Gemini program.)

3.2 Dynamics

In this section, we present the dynamical analysis of the above described photometrically identified structure, based on the redshifts obtained.

3.2.1 Redshift Distribution and Velocity Dispersion

In Figure 2, the full redshift distribution of all galaxies is shown as the dotted open histogram. There are two main peaks in the full distribution: one corresponds to the centre of the main cluster, and the other corresponds to RXJ1347-SW. We analyze these two clusters in detail first in this section, and examine the dynamics of the large-scale structure in the next section.

The redshift distribution of galaxies within ~ 1.4 Mpc from the main cluster centre is shown as the shaded histogram. The distribution is smooth in general; there is an indication of two separate peaks, but the distribution is still consistent with being drawn from the single Gaussian overplotted on the shaded histogram in Figure 2. In particular, a χ^2 test shows that a subsample drawn from this single Gaussian distribution would have a χ^2 value as large as we observed about 80 per cent of the time. The mean redshift we measure is 0.4513 ± 0.0006 , consistent with the previous measurement by Cohen & Kneib (2002). The dispersion we measure, using the bi-weight method of Beers et al. (1990), with 3σ clipping applied, is 0.0056 ± 0.0005 , which corresponds to a rest-frame velocity dispersion of 1163 ± 97 km s $^{-1}$. The errors are estimated using Jackknife resampling (Wall & Jenkins 2003). From now on, we refer to galaxies that are within 3 times the dispersion as members of the main cluster. The velocity dispersion we measure is higher than that of Cohen & Kneib (2002) (we discuss this more in §4.1.1).

Despite the consistency with a single Gaussian there is an indication of two separate velocity peaks in the distribution. A χ^2 test shows that, at the ~ 30 per cent level, the distribution is consistent with a combination of two Gaussian functions: one with $\bar{z}_1 = 0.4495$ and rest-frame velocity dispersion $\sigma_1 = 620$ km/s, and the other with $\bar{z}_2 = 0.4552$ and $\sigma_2 = 535$ km/s. In that case, the centre of the cluster would be composed of two separate components with much smaller masses, and a relative velocity of ~ 1000 km s $^{-1}$; considerably larger than the < 100 km/s difference between the two BCGs ($z_1 = 0.4515$ and $z_2 = 0.4511$). Although statistically this model is not favoured over the single-population model, we cannot rule out the possibility that there are two distinct dynamical components. We revisit this further in §4.1.2 when we consider both the spatial and velocity distribution of galaxies.

The redshift distribution of RXJ1347-SW (pointing “SW”) is shown as the open solid histogram in Figure 2. It is not significantly different from a Gaussian distribution, with a mean redshift of 0.4708 ± 0.0006 , and dispersion of 0.0038 ± 0.0005 , or 780 ± 100 km s $^{-1}$.

3.2.2 Phase Space Distribution

We examine the dynamics of the large-scale structure by converting the redshift of each galaxy to a rest-frame velocity relative to the central redshift of the main cluster. In Figure 3 we show the velocity offset as a function of position projected along the line connecting the main cluster and RXJ1347-SW. Galaxies in the inner region of the cluster mainly occupy regions spanning from -2000 km s $^{-1}$ to 2000 km s $^{-1}$, symmetrically, while RXJ1347-SW is at ~ 4000 km s $^{-1}$ from the main cluster. Note that in velocity space, the

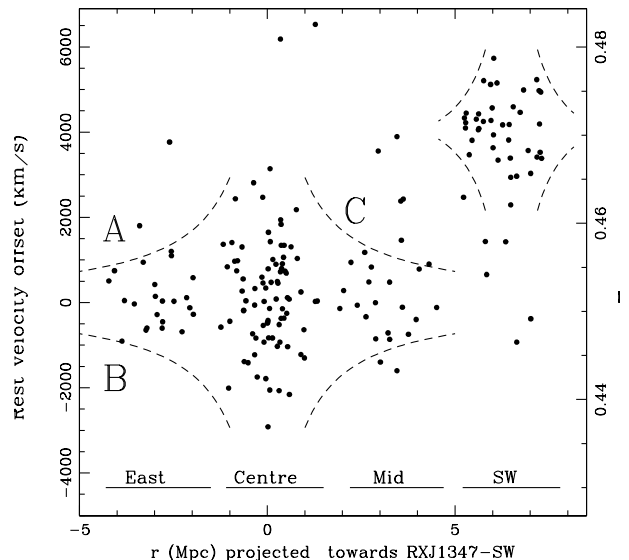


Figure 3. The rest frame velocity offset as a function of distance relative to the cluster centre projected along the line towards RXJ1347-SW. The dashed curves indicate the boundary of the caustics. See text for details.

region occupied by members of massive clusters resembles a trumpet shape, as expected in a spherical infall model (e.g. van Haarlem & van de Weygaert 1993). The dashed curves in Figure 3 indicate the boundary of the caustics for these two systems (as will be discussed in §3.4.1), derived analytically from equation (7) in Diaferio (1999) assuming the two systems follow a NFW profile (Navarro et al. 1997). In pointing “East”, on the other side of the main cluster away from RXJ1347-SW, there are almost no galaxies in the regions labelled “A” and “B” in Figure 3 around the cluster above the caustic curve. In comparison, there are ~ 8 galaxies occupying the region between the main cluster and RXJ1347-SW, labelled “C”. Given that our redshift completeness is about 50 per cent, we expect there are approximately twice as many $i' < 22$ galaxies (~ 16) within that region in total. Note this is not a sampling bias, because the pointing “East” and “Mid” are located symmetrically on two sides of the main cluster. Also, the uncertainties on the redshift determination, or the position of the caustic curve, would not change the fact that there is an excess of galaxies between the main cluster and RXJ1347-SW. In §4.2 we will use simulations to investigate whether these galaxies are physically residing in regions between the main cluster and RXJ1347-SW, and thus suggest a possible structure connecting the two systems.

3.3 Colour Distribution

As described in §3.1, we trace the large-scale structure around this cluster using red-sequence galaxies. We consider galaxies in the redshift range $\bar{z}_{cl} - 3\sigma_{cl} < z < \bar{z}_{sw} + 3\sigma_{sw}$ as associated with the structure, where \bar{z}_{cl} and σ_{cl} are the mean and dispersion of the redshift distribution of the main cluster, and \bar{z}_{sw} and σ_{sw} are the same for RXJ1347-SW. In Figure 1, solid squares and crosses represent red and blue

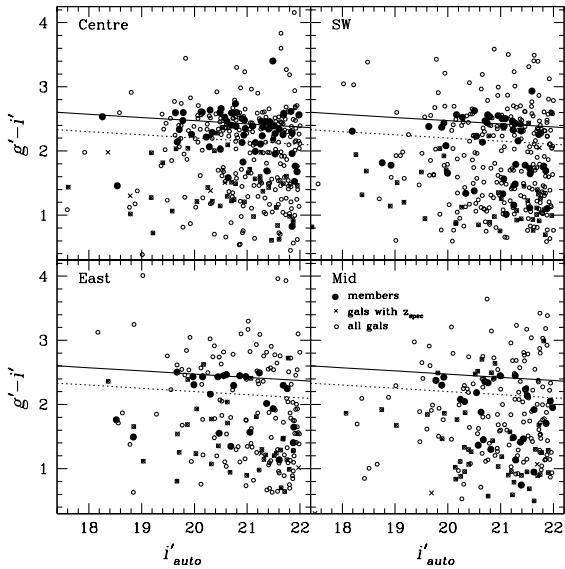


Figure 4. The colour-magnitude diagram of galaxies is shown for each of the four pointings we targeted, along the elongated structure. Open circles are all galaxies in the field of view, crosses are galaxies with secure redshifts, and filled circles are members associated with the structure. Solid lines are fitted red-sequences, and dashed lines separate blue galaxies from the red-sequence (see text for detail).

galaxies that are spectroscopically confirmed to be associated with the structure, respectively.

The study by Butcher & Oemler (1984) revealed a higher fraction of blue galaxies in high redshift clusters compared to local ones (the Butcher-Oemler effect), indicating on-going star formation in high redshift clusters. Since then there have been many studies on the dependence of this effect on the environment, and cluster properties such as the X-ray temperature (e.g. Urquhart et al. 2009; Wake et al. 2005). RX J1347-1145 is the most X-ray luminous cluster known, and has an elongated large-scale structure; therefore it is interesting to explore the colour distribution of the galaxies in this structure. The colour-magnitude diagram of galaxies in the four pointings along the structure is shown in Figure 4. Open circles are all galaxies in the field of view, crosses are galaxies with secure redshift obtained, and filled circles are members associated with the structure.

We calculate the blue fraction of the main cluster using the Butcher & Oemler (1984) criterion, i.e. galaxies 0.2 mag bluer than the CMR in rest-frame (B-V). We transform rest-frame $\Delta(B - V) = 0.2$ into our observed $\Delta(g' - i')$ using the colour difference between E and Sab galaxies from Fukugita et al. (1995), as indicated by the dashed lines in Figure 4. The number of blue cluster members is calculated by dividing the number of spectroscopically confirmed blue galaxies by the completeness of the spectroscopy for the blue population. The number of red cluster members is calculated in the same way, and the total number of members is then the sum of that of the blue and red galaxies. The blue fraction of RX J1347-1145 within the central 1.4 Mpc ($\sim 0.8r_{200}$), down to $i' = 21$ (corresponding to $M_V \sim -20$) is $20^{+9}_{-8}\%$. The uncertainty is estimated us-

ing the weighted binomial statistics Gehrels (1986). Note although RX J1347-1145 is the most X-ray luminous cluster in the RASS, its blue fraction in the central region is similar to that of other less luminous clusters (Ellingson et al. 2001), consistent with the lack of X-ray luminosity dependence found by Wake et al. (2005). The blue fraction of the cluster RXJ1347-SW ($36^{+13}_{-12}\%$) is, within the uncertainty, consistent with that of the main cluster.

From the contours in Figure 1, the region between the main cluster and RXJ1347-SW shows an overdensity of red-sequence galaxies. Our spectroscopy also reveals a large population of blue galaxies, and it is interesting to note that they form two trails running in the same direction as the elongation of the large-scale structure. The large blue population associated with an overdensity of red galaxies is particularly interesting. It suggests that targeting regions with overdensities of red-sequence galaxies for spectroscopic follow-up is a strategy that allows the efficient selection of cluster members, while still tracing interesting structures with active star formation. A more thorough analysis of the stellar populations in the large-scale structure will be done when the rest of the data are obtained.

3.4 Mass Estimate

In this section, we estimate the mass of the main cluster and RXJ1347-SW using different methods. We defer a comparison with the literature, and the discussion of the dynamical implication, to §4.1.

3.4.1 Dynamical Estimates

For a given density profile and velocity anisotropy, the velocity dispersion can be used to infer the virial mass. Under the assumption of a singular isothermal density profile and a velocity anisotropy that satisfies $\sigma = v_c/\sqrt{2}$ (Lokas & Mamon 2001), the virial mass can be expressed as $M_v = 2\sigma_1^2 r_v / G$. Applying this to the measured velocity dispersion (§3.2.1) yields a $M_{200} = \sqrt{2}\sigma_1^3 / [5H(z)G] = 1.16^{+0.32}_{-0.27} \times 10^{15} M_\odot$, with $r_{200} = \sqrt{2}\sigma / [10H(z)] = 1.85$ Mpc. This mass estimate agrees well with that inferred from the richness of the cluster, as described in §3.1.

Under the same assumptions, the mass of RXJ1347-SW is estimated to be $M_{200} = 3.4^{+1.4}_{-1.1} \times 10^{14} M_\odot$, with $r_{200} = 1.22$ Mpc. This M_{200} is also in good agreement with that inferred from the richness, and confirms that the cluster RXJ1347-SW we detected photometrically using the red-sequence galaxies is indeed a massive cluster. There has not been any report on the existence of this cluster in the literature.

Another method to estimate the mass through dynamical analysis is the caustic technique, under the assumption that clusters form through hierarchical accretion (Diaferio & Geller 1997; Diaferio 1999). The advantage of this technique is that it does not depend on the assumption of dynamical equilibrium, and it can probe the mass out to large radii where the virial theorem does not apply any more.

As described in §3.2.2 (Figure 3), cluster members occupy a region in velocity space with a trumpet shape delineated by caustics that separate them from the Hubble flow.

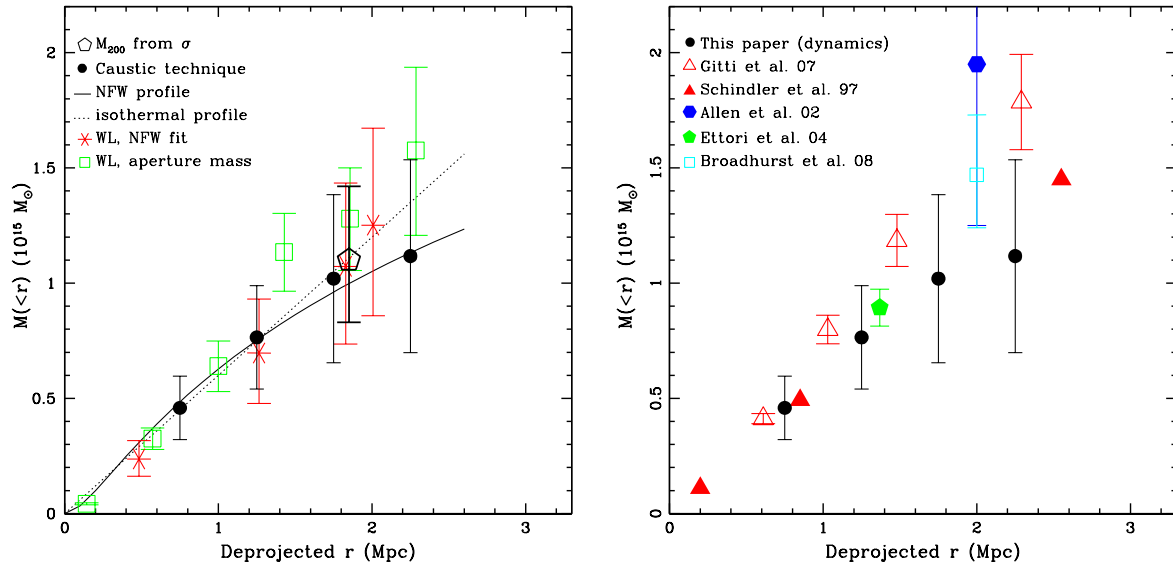


Figure 5. The deprojected mass profile for RX J1347-1145. Left panel: the black points represent the mass profile inferred from the caustic method. The solid, and dotted curves show the fitted NFW and isothermal profile respectively. The stars and open squares are our weak lensing analysis. Right panel: the black points are the same as in the left panel. The other symbols are mass estimates from the literature.

Assuming spherical symmetry, the mass of the cluster can be estimated as:

$$M(< r) = \frac{1}{2G} \int_0^r \mathcal{A}^2(r) dr, \quad (1)$$

where \mathcal{A} is the amplitude of the caustic. The prescription for implementing the caustic method is described in detail in Diaferio (1999). Here we only summarize the key steps. Since the location of the caustics is where clusters are separated from the Hubble flow, it is indicated by a significant drop of the density of cluster members in velocity space. Therefore, one first calculates the density as a function of velocity at different radii, using an adaptive kernel method (Silverman 1986). In order to use the spherical smoothing window, the window size in velocity and distance, h_v and h_r , has to be rescaled (see Diaferio 1999, for details). For our data, we choose $q = h_v/h_r = 6$, and a spherical smoothing window size of $\sim 700 \text{ km/s}^1$. In the central region of clusters, the escape velocity (essentially the location of the caustics) is twice the velocity dispersion, which is valid under the assumption that the central region of the cluster is virialized. Therefore, in practice, the threshold density where the significant drop occurs (and thus determines the amplitude of the caustics) is chosen so that the above condition is satisfied.

The deprojected mass profile of the main cluster estimated using this technique is shown as solid dots in both panels of Figure 5. The errors are estimated using Jackknife resampling (Wall & Jenkins 2003). At $r_{200} = 1.85 \text{ Mpc}$ the enclosed mass is $\sim 1 \times 10^{15} M_\odot$. This is in excellent agreement with that inferred from the velocity dispersion; how-

ever, this is largely true by construction, since the density threshold is chosen such that the two techniques agree within the virialized region of the cluster. The caustic-based measurements have the most value at larger radii, where the assumption of virial equilibrium is unlikely to hold. Note beyond $r \sim 2 \text{ Mpc}$, we only have sparse sampling in two pointings, and the velocity distribution of galaxies in these pointings is not likely representative of that of the whole population at that radius, due to the presence of elongated large-scale structure. We fit the mass profile to a NFW (Navarro et al. 1997) and isothermal profile, shown as the solid and dotted curves respectively in the left panel of Figure 5². Because of the large uncertainties on the mass profile due to limited data, the two profiles cannot be distinguished.

3.4.2 Weak Lensing Analysis

We use the deep CFHT r' imaging data to study the cluster mass distribution using weak gravitational lensing. Unlike dynamical methods, the weak lensing signal provides a direct measurement of the *projected* mass, irrespective of the dynamical state of the cluster. Furthermore, the observed signal can be used to “map” the distribution of dark matter (e.g. Kaiser & Squires 1993).

Our cluster weak lensing analysis follows in detail the steps described in Hoekstra (2007). In order to relate the lensing signal to a physical mass requires knowledge of the redshift distribution of the sources. The wavelength coverage and limited depth of the observations prevent us from deriving accurate photometric redshifts for the individual sources. Instead we use the results from Ilbert et al. (2006)

¹ Within the range of reasonable choices of parameters, the change of the resulting mass profile is within the resulting error bars.

² The fitted NFW profile is used in the analytic derivation of the caustic curves shown in Figure 3 and discussed in §3.2.2.

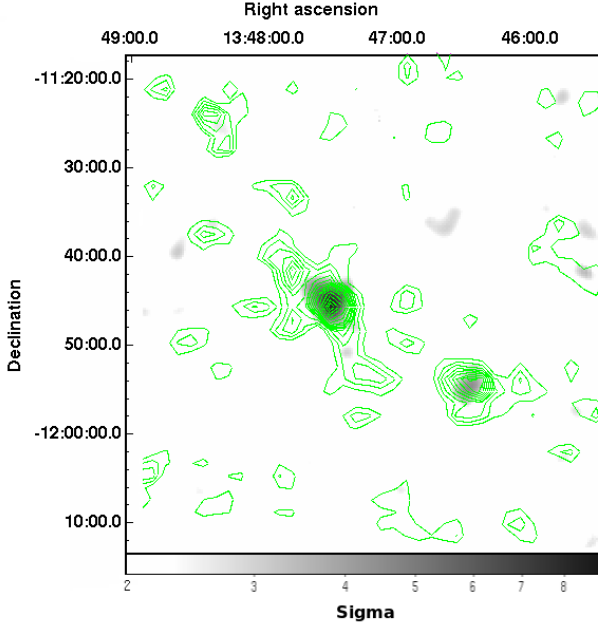


Figure 6. The grey scale shows the weak-lensing signal-to-noise map, out to ~ 10 Mpc from the main cluster centre. Contours of the red galaxy surface density (as in Figure 1) are overlaid, starting from 2σ with an interval of 1σ . The two prominent peaks are the main cluster and RXJ1347-SW; their mass concentrations coincide with the overdensities of the red-sequence galaxies.

who determined photometric redshifts for galaxies in the CFHTLS deep fields.

To determine the lensing signal, we measure the shapes of galaxies with $22 < r' < 25$. We use such a relatively faint cut because of the high redshift of the cluster. The galaxy shapes are corrected using the method presented in Kaiser et al. (1995), with modifications described in Hoekstra et al. (1998). The weak lensing signal is sensitive to all structure along the line-of-sight and, as shown in Hoekstra (2001, 2003), this distant (uncorrelated) large-scale structure introduces additional noise to the mass estimate. This ‘cosmic shear’ noise is included in the errors listed below. We note that the noise due to the intrinsic ellipticities of the sources dominates because of the relatively high cluster redshift.

The weak lensing reconstruction of the projected surface density with a smoothing scale of $123.3''$ is presented in Figure 6³ out to ~ 10 Mpc. To indicate more clearly which structures are significant, we show the signal-to-noise ratio, rather than the signal itself, as the grey scale (see the left panel in Figure 9 for a more detailed view). The main cluster and RXJ1347-SW are clearly detected, at $\sim 8\sigma$ and $\sim 4\sigma$ levels respectively. No other significant structures are evident in this map. The contours of the overdensity of the red-sequence galaxies, the same as in Figure 1, are overplotted on top of the mass map. For the main cluster and RXJ1347-SW, the mass concentrations coincide with the overdensities of red-sequence galaxies.

³ The map presented in this Figure was constructed using source galaxies with $23 < r' < 25.5$

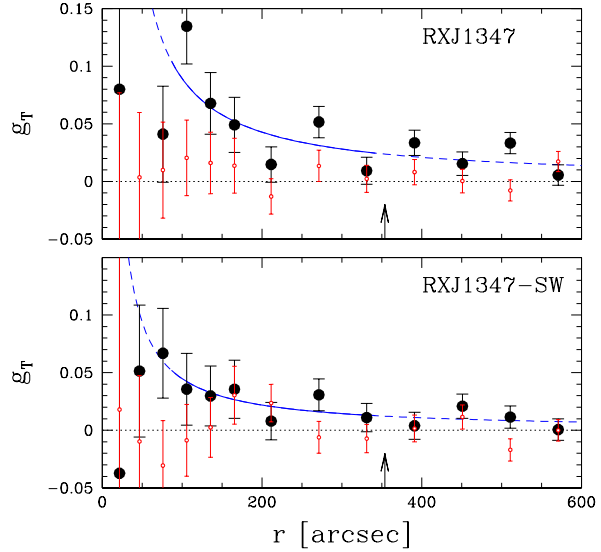


Figure 7. Tangential distortion as a function of the distance from the cluster center for the main cluster (top panel) and RXJ1347-SW (bottom panel). In both cases we detect a significant lensing signal out to large radii (the arrows indicate 2 Mpc). The open points correspond to the signal that is measured when the sources are rotated by 45 degrees, which provides a measure of the level of systematics. The points are consistent with zero. The blue dashed line shows the best fit SIS model, where the solid blue part indicates the region to which the model was fit. The errorbars indicate the statistical error in the measurement, due to the intrinsic ellipticities of the sources (see Hoekstra et al. 2000 for details).

The smoothing of the mass map limits its use to determine the cluster mass. Instead, we compute the mean tangential distortions as a function of distance from the cluster center. The resulting measurements for the main cluster and RXJ1347-SW are shown in Figure 7. We estimate the cluster masses from these shear measurements using two different methods. The first, and most commonly used, is to assume a density profile and determine the best fit parameters to the observed tangential distortion. For comparison with the dynamical results, we first fit a singular isothermal sphere model (SIS) to the observations between 500 kpc and 2 Mpc, which yields a velocity dispersion of $\sigma = 1282 \pm 124$ km/s, in excellent agreement with the results based on the redshifts of the cluster galaxies. Thanks to the wide-field lensing data, we can also apply the same method to RXJ1347-SW (centred at $13^{\text{h}}46^{\text{m}}27.2^{\text{s}}$, $-11^{\circ}54'20.2''$), for which we obtain a velocity dispersion of $\sigma = 927 \pm 165$ km/s, also in good agreement with the value inferred from the redshifts of the cluster members.

Although the SIS allows for an easy comparison to the observed velocity dispersion, a more physically motivated function is the NFW (Navarro et al. 1997) profile, which has been inferred from numerical simulations. We assume the mass-concentration relation from Duffy et al. (2008) and fit the NFW model to the data within 500 kpc and 2 Mpc. With these assumptions, we find a best-fit value for the virial mass of $M_{\text{vir}} = 1.89^{+0.59}_{-0.55} \times 10^{15} M_{\odot}$. The best fit NFW model within different apertures are indicated by stars

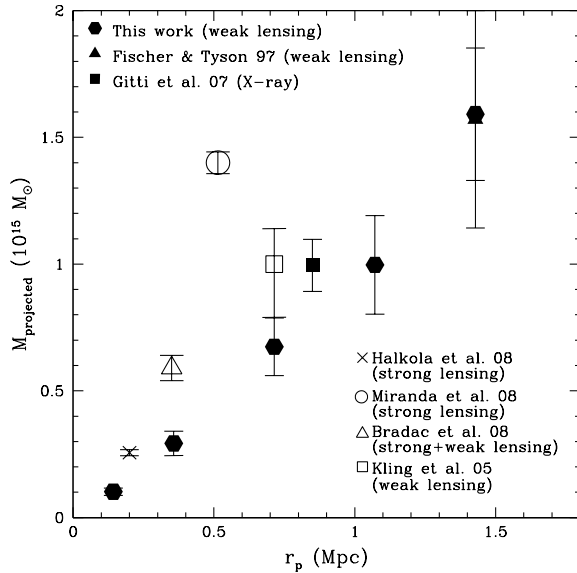


Figure 8. The projected mass as a function of radius for RX J1347-1145. The solid hexagons are estimates from this work, and the other symbols are from the literature. See text for details.

in the left panel of Figure 5. For RXJ1347-SW we obtain $M_{\text{vir}} = 6.4^{+3.9}_{-3.3} \times 10^{14} M_{\odot}$.

To compare to the results from the cluster galaxy dynamics, we also compute the corresponding masses within $r_{200}^{\text{dyn}} = 1.85$ Mpc. For this choice of radius we obtain $M_{200} = 1.47^{+0.46}_{-0.43} \times 10^{15} M_{\odot}$ for the main cluster. This result is in excellent agreement with the value inferred from dynamics. For RXJ1347-SW we obtain $M_{200} = 4.8^{+2.9}_{-2.5} \times 10^{14} M_{\odot}$ for $r_{200}^{\text{dyn}} = 1.22$ Mpc.

Since weak lensing signals are sensitive to the total mass projected along the line-of-sight; it is interesting to consider a non-parametric estimate for the projected mass within an aperture (e.g. Clowe et al. 1998; Fahlman et al. 1994; see Hoekstra (2007) for our implementation). The resulting *projected* masses as a function of radius are presented in Figure 8 as solid hexagons. Figure 8 also shows other estimates from the literature, which will be discussed in detail in §4.1.1.

As discussed in Hoekstra (2007) and Mahdavi et al. (2008) one can assume spherical symmetry to deproject the resulting masses. We assume an NFW profile to extrapolate along the line-of-sight, but note that the results at large radii do not depend strongly on this assumption. The resulting deprojected masses are shown as open squares in the left panel of Figure 5. They are consistent with our dynamical mass estimate using the velocity caustics, within the uncertainties.

Within an aperture of $r_{200}^{\text{dyn}} = 1.85$ Mpc, we find a deprojected mass for the main cluster of $M_{200} = 1.25 \pm 0.19 \times 10^{15} M_{\odot}$, again in excellent agreement with the dynamical measurements. Similarly we find a mass of $M_{200} = 5.6 \pm 1.6 \times 10^{14} M_{\odot}$ for RXJ1347-SW using $r_{200}^{\text{dyn}} = 1.22$ Mpc, which is somewhat larger than the dynamical mass.

4 DISCUSSION

4.1 Dynamical State of the Main Cluster

The mass estimate and the dynamical state of this cluster have been the focus of many previous studies. In this section, we first compare the mass estimated using different methods in this work and in the literature, and then discuss the dynamical state of the cluster.

4.1.1 Comparison of Mass Estimates

The mass of RX J1347-1145 has been estimated using different techniques. Other than through the dynamics and weak lensing signals as described in §3.4, X-ray data have also been used to infer the mass.

In a recent study by Gitti et al. (2007), they estimate the mass by finding a NFW mass profile (Navarro et al. 1997) that reproduces the observed X-ray temperature profile. The resulting integrated mass at different radii are plotted as open triangles in the right panel of Figure 5. This is consistent with our estimates from both the dynamics and the weak lensing analysis (§3.4).

Similarly, the study by Allen et al. (2002) estimated the virial mass by fitting a NFW profile to their Chandra observations, and their M_{200} is plotted as the solid hexagon in the right panel of Figure 5. Other mass estimates using X-ray data by Schindler et al. (1997) and Ettori et al. (2004) are plotted in the right panel of Figure 5 as well. All these estimates at different radii are consistent within their error bars.

As discussed in §3.4.2, the projected mass is a more direct measurement than the *deprojected* mass from the weak lensing analysis, since it is the total projected mass along the line-of-sight that gives rise to the weak lensing signals; therefore, it is more direct to compare the measured projected mass from different studies.

In Figure 8, the projected mass enclosed within a certain radius estimated from strong, weak, and combined lensing analyses in the literature are plotted, along with our weak lensing estimate (see legends). Our weak lensing mass estimate (solid hexagons) is consistent with that of Fischer & Tyson (1997) (the solid triangle), and these two estimates are themselves in agreement with the X-ray analysis of Gitti et al. (2007) (the solid square).

The weak lensing mass estimate by Kling et al. (2005) is slightly higher ($\sim 2\sigma$). This discrepancy is likely due to differences in the assumed source redshift distribution; Kling et al. (2005) base their estimate on $r < 24.5$ spectroscopy over the small area of the Hubble Deep Field, while we use the photometric redshift distribution from the CFHTLS Deep survey. Given our good agreement with both X-ray and dynamical mass estimates, it seems likely that their analysis underestimates the mean source redshift, and thus overestimates the cluster mass.

In comparison, the mass estimates from strong lensing studies (Halkola et al. 2008; Miranda et al. 2008) and the combined strong and weak lensing analysis by Bradač et al. (2008) are systematically higher⁴. In general strong lensing

⁴ We did not include the work by Sahu et al. (1998) because the redshift of the arc they assumed is not correct.

provides an accurate estimate of the projected mass only within the central few hundred kpc, whereas the weak lensing mass is better constrained at larger radii; therefore caution should be taken when combining strong and weak lensing analysis. See also Halkola et al. (2008) for a summary and more discussion of the comparison among these works.

The good agreement shown in Figures 5 and 8 suggest that the mass estimated from dynamical, X-ray, and weak lensing studies is generally consistent, while strong lensing gives a slightly higher value.

So far, there has been only one other published redshift survey on this cluster, by Cohen & Kneib (2002). They derived from 47 cluster members in their sample a velocity dispersion of $910 \pm 130 \text{ km s}^{-1}$, using the same bi-weight method by Beers et al. (1990) as used in this work. This is lower than the value we derived, and thus leads to a lower mass that is in conflict with that from other methods. However, we believe that the value quoted in their paper is in error. When we reanalyze the 47 redshifts as given in their Table 1, we obtain a velocity dispersion of $1098 \pm 157 \text{ km s}^{-1}$. Therefore, there is actually no discrepancy between the dynamical mass estimate and that from X-ray and lensing analysis.

4.1.2 Merger in the centre?

One important reason the merger scenario was proposed for this cluster is to explain the large discrepancy between the mass estimated from the velocity dispersion by Cohen & Kneib (2002) and the X-ray and lensing mass estimates discussed in the above section. However, as shown above, our new measurement resolves this discrepancy, and thus removes the original motivation for believing the system is undergoing a major merger.

Nonetheless, there is other evidence suggesting that this cluster might have recently undergone a merger. Although the X-ray morphology is generally relaxed in the centre of the cluster, the existence of a region with shocked gas $\sim 10\text{--}20 \text{ arcsec}$ ($\sim 0.09 \text{ Mpc}$) SE of the cluster centre has been detected as a high-pressure region in X-ray observations (Allen et al. 2002; Gitti & Schindler 2004; Ota et al. 2008; Bradač et al. 2008; Miranda et al. 2008) and a strong decrement in the Sunyaev-Zel'dovich observations (Komatsu et al. 2001). Also, Miranda et al. (2008) found that their strong lensing data can be much better described by a two component model with comparable mass than the single mass component model. The fact that there are two very bright galaxies in the centre of this cluster $18''$ ($\sim 0.1 \text{ Mpc}$) apart in the plane of sky is also taken as a possible indication of a merger event (but note their line-of-sight relative velocity is only $\lesssim 100 \text{ km/s}$). Kitayama et al. (2004) suggested that one possible scenario is a collision of equal mass clumps with a collision speed of 4600 km s^{-1} . However, this collision cannot be mostly along the line-of-sight, because as shown in §3.2.1 (and also in the work by Cohen & Kneib 2002), the redshift distribution is better described as a single Gaussian distribution. As discussed in §3.2.1, our velocity data are also consistent (at the 30% significance level), with a model distribution having two Gaussian components. However, even in that case, the radial velocity offset between the two peaks is only about 1000 km s^{-1} , much smaller than 4600 km s^{-1} . Furthermore, if the

centre of the cluster is indeed composed of two merging components, each with a much smaller velocity dispersion than what we find for the system as a whole (see §3.2.1), the dynamically-estimated mass profile would be much lower than that shown in Figure 5 (the hexagon and the filled points), and that would be inconsistent with the weak lensing and X-ray mass estimates.

To investigate this further, we use the Δ -test proposed by Dressler & Shectman (1988) to examine closely the 3D substructures in the centre of the main cluster. This test measures the deviation of the local velocity and velocity dispersion from the global mean, and is quantified as :

$$\delta^2 = \frac{N_{nb} + 1}{\sigma^2} [(\bar{v}_{local} - \bar{v})^2 + (\sigma_{local} - \sigma)^2], \quad (2)$$

where N_{nb} is the number of neighbour galaxies, \bar{v}_{local} and σ_{local} are local mean velocity and dispersion measured from each galaxy and its N_{nb} nearest neighbours, and \bar{v} and σ are global mean velocity and velocity dispersion, respectively.

In the left panel of Figure 9, we show the spatial distribution of the confirmed cluster members (solid squares) with their local deviation from the global mean indicated by the size (proportional to δ) of the circle around them. The solid circles indicate negative local deviations ($\bar{z} < 0.4513$), and dashed open circles positive local deviations ($\bar{z} > 0.4513$). To examine closely the centre of the cluster, in this panel we only plot the region within a radius of $\sim 0.5 \text{ Mpc}$ from the cluster centre. The two triangles indicate the two BCGs. The region $\sim 20 \text{ arcsec}$ SE of cluster centre, indicated by the large green filled circle, is where the shocked gas is detected. Around that region, we do not detect significant deviation from the global mean. However, there seems to be a hint of a segregation between the region NE and SW of the cluster centre, in the sense that in the NE region most galaxies have negative local mean velocity relative to the mean redshift of the cluster, while galaxies in the SW region mostly have positive local mean relative velocity. This segregation is along the same direction connecting the main cluster and RXJ1347-SW.

Note the above estimated local mean might be biased by a few galaxies with large deviations due to our sparse data sampling. Therefore, in the right panel of Figure 9, we examine directly the spatial distribution of the redshift of individual galaxies, with a field of view of $\sim 2 \text{ Mpc} \times 2 \text{ Mpc}$. The open circles indicate possible potential members (not targeted), and the crosses represent nonmembers. Cluster members with $z < 0.4513$ are indicated by the blue solid squares, and members with $z > 0.4513$ are indicated by the red solid squares. There is a hint that more galaxies with negative relative velocity reside in the region NE to the cluster centre. To test whether the distribution of the two samples is significantly different, we apply a 2-dimensional Kolmogorov-Smirnov test following the procedure proposed by Peakcock (1983). The test suggests that there is a ~ 60 per cent probability that galaxies with negative and positive relative velocity have different spatial distributions.

The above evidence discussed in this section suggests that this might be a merger more in the plane of the sky than along the line-of-sight. However, with the lack of both a clear sharp shock front and a distinct separation of mass concentration on both sides of the shock (see contours in the left panel of Figure 9), as observed in the famous example

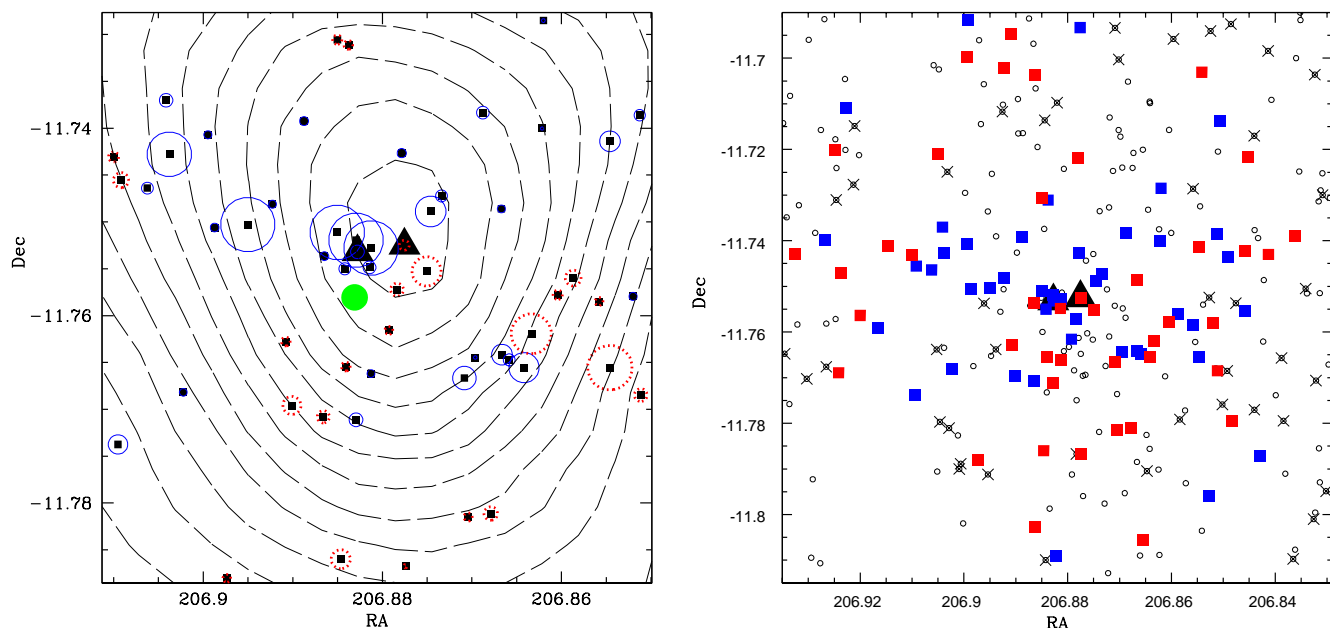


Figure 9. Left panel: the spatial distribution of galaxies in the centre of the main cluster (the field of view is $\sim 1 \text{ Mpc} \times 1 \text{ Mpc}$), with the contours of the weak lensing signal-to-noise mass map overlaid, with an interval of 0.5σ . For clarity, we only plot the confirmed cluster members (the solid squares). The two triangles indicate the two BCGs. The size of the open circles (proportional to δ) around the cluster members show the local deviation from the global mean, with solid open circles indicating negative local deviations ($\bar{z} < 0.4513$) and dashed open circles positive local deviations ($\bar{z} > 0.4513$). The big filled green circle indicates the region $\sim 20 \text{ arcsec}$ SE from cluster centre, where the shocked gas is detected. See text for details. Right panel: the spatial distribution of galaxies in the centre of the cluster, with a field of view of $\sim 2 \text{ Mpc} \times 2 \text{ Mpc}$. The open circles indicate possible potential members (not targeted), the crosses indicate nonmembers, the blue solid squares represent confirmed members with $z < 0.4513$, and the red solid squares represent confirmed members with $z > 0.4513$. Again the two triangles indicate the two BCGs.

of merger in the plane of the sky, the Bullet cluster (e.g. Markevitch et al. 2002; Clowe et al. 2006), the exact merger scenario still needs closer examination both in observations and simulations.

4.2 A possible filamentary connection

As seen in Figure 3, cluster RXJ1347-SW is $\sim 7 \text{ Mpc}$ (projected in the plane of sky) away from the main cluster, and has a rest-frame velocity offset of $\sim 4000 \text{ km s}^{-1}$ relative to the main cluster. This could be a result of two scenarios. One is that RXJ1347-SW is at nearly the same distance as the main cluster, and is falling into the cluster at a speed of $\sim 4000 \text{ km s}^{-1}$. The other is that it is $\sim 25 \text{ Mpc}$ in the background moving with Hubble expansion. We resort to simulations to try distinguishing these two scenarios. Since what we are looking for is how likely it is for two clusters like RX J1347-1145 and RXJ1347-SW to have a relative peculiar velocity as large as observed, we use the Hubble volume simulations (Evrard et al. 2002) because of its large box size ($3000^3 h^{-3} \text{ Mpc}^3$).

From the cluster catalogue in the full-sky light cone with ΛCDM cosmology ($\Omega = 0.3$, $\Lambda = 0.7$, $\sigma_8 = 0.9$), we search, in a redshift range close to the redshift of RXJ1347, for a pair of clusters that have similar masses ($M1 \gtrsim 1 \times 10^{15} M_\odot$, $M2 \gtrsim 1 \times 10^{14} M_\odot$), projected distance ($\sim 10 \text{ Mpc}$), and rest-frame velocity offset as RX J1347-1145 and RXJ1347-SW. We do not find any system where they are at the same distance, but

with an observed velocity offset of $\sim 4000 \text{ km s}^{-1}$. This does not mean definitely that no system could have such a large relative peculiar velocity, because this is based on only one simulation with a large but still limited volume, under the assumption of one particular set of cosmological parameters. Among these parameters, σ_8 is the most uncertain one, and in fact a lower value than used in the simulation is preferred by the latest WMAP measurement (Dunkley et al. 2009). However, in that case, the peculiar velocity between clusters would be even lower due to the lower attracting force from the lower mass density. Even though we cannot reach a definitive conclusion, this does suggest that the probability that RXJ1347-SW is falling into the main cluster with such a high velocity is low; instead, it is more likely to be in the background.

However, just because RXJ1347-SW is far in the background does not necessarily mean that there is no connection between it and the main cluster. The fact that we observed an excess of galaxies between the two in velocity space (Figure 3) suggests there might be a physical connection (see Tanaka et al. 2009 for a report of the spectroscopic detection of a large-scale galaxy filament associated with a massive cluster at $z = 0.5$; also Ebeling et al. 2004). We compare our observation with simulations to see if the observed excess of galaxies could represent a real large-scale filamentary structure connecting the main cluster and RXJ1347-SW, rather than foreground and background galaxies *projected* in velocity space. To examine this on the scale of individ-

ual galaxies, we make use of the galaxy catalogue from a semi-analytic model by Font et al. (2008)⁵ based on the high resolution Millennium simulation (Springel et al. 2005). Because of the small volume of the simulation, there are only four clusters that have mass greater than $1 \times 10^{15} M_{\odot}$. We search around these four clusters for a second cluster with lower mass and at a similar distance projected in the plane of sky and along the line-of-sight from the more massive cluster as in the case of our observed RX J1347-1145 and RXJ1347-SW. For the four pairs of systems we found, we calculate the line-of-sight velocity offset of each galaxy relative to the more massive cluster, and plot it as a function of distance, projected along the direction towards the less massive one. For direct comparison with our observed data, we only plot galaxies in a strip with a width similar to the radius of the FOV as our spectroscopic observation, down to the same magnitude limit as our data. In Figure 10 we show one extreme case, where the two clusters ($M_1 \sim 3 \times 10^{15} M_{\odot}$, $M_2 \sim 2 \times 10^{15} M_{\odot}$) are connected by a physical, large-scale filament traced by galaxies, with two other clusters in between. This structure is clearly visible in velocity space. The triangles indicate galaxies that are spatially within a cylinder with a radius of 3 Mpc (comparable to the virial radius of the more massive cluster) connecting the two clusters. This is an extreme case where the galaxy filament is very impressive due to the presence of two other massive systems in between the two clusters. However, even in other cases in the simulation where the excess of galaxies between two clusters is smaller ($\sim 5-10$) than this one, the excess is still due to galaxies that *physically reside* in the region between two clusters, instead of being purely due to a *projection* effect. Although this is not definitive, it does support the possibility that the excess of galaxies we observe in velocity space between the two clusters reflects a real physical structure.

5 SUMMARY

In this work, we presented photometric and spectroscopic analysis on the dynamics and large-scale structure around the most X-ray luminous cluster RX J1347-1145, and found the following results:

- We identified an elongated large-scale structure around the main cluster, photometrically using red-sequence galaxies, and discovered a rich cluster (RXJ1347-SW) ~ 7 Mpc (projected) away from the main cluster.
- The velocity dispersion of the main cluster is 1163 ± 97 km s⁻¹, corresponding to $M_{200} = 1.16^{+0.32}_{-0.27} \times 10^{15} M_{\odot}$, with $r_{200} = 1.85$ Mpc.
- Our dynamical mass estimates based on both the velocity dispersion and velocity caustics are consistent with our weak lensing analysis, and the X-ray studies in the literature. We also find excellent agreement between these mass estimates and that estimated photometrically from the abundance of red-sequence galaxies (the richness).
- Our new measurement resolves a previous claimed discrepancy between the dynamical mass estimate and other methods Cohen & Kneib (2002).

⁵ Note for our purpose here the exact semi-analytic model used is unimportant.

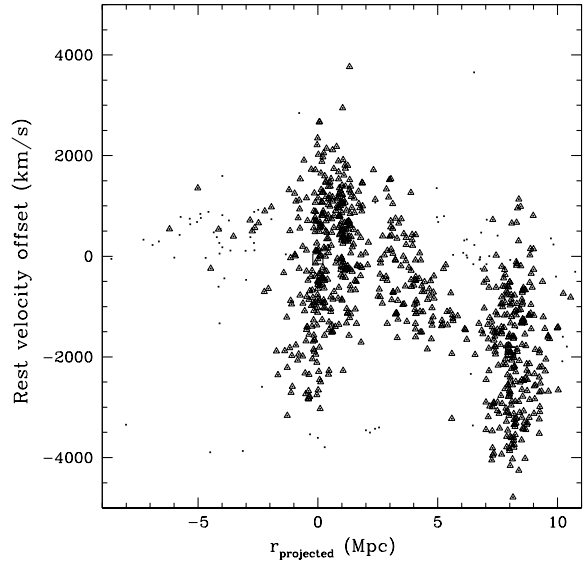


Figure 10. This figure shows the rest-frame velocity offset of galaxies around two simulated clusters, as a function of distance projected in the direction connecting the two. The two clusters ($M_1 = 2.7 \times 10^{15} M_{\odot}$, $M_2 = 1.8 \times 10^{15} M_{\odot}$) are connected by a real physical filament traced by galaxies, with two other clusters in between. The excess of galaxies between them in velocity space is clearly visible. The two squares indicate the centres of the two clusters, and the triangles indicate galaxies that are spatially within a cylinder with a radius of 3 Mpc connecting the two clusters.

- Our spectroscopic analysis confirmed that the photometrically identified structure RXJ1347-SW is indeed a massive cluster, with a velocity dispersion of 780 ± 100 km s⁻¹.
- Our weak lensing analysis shows good correspondence between the mass concentration and the overdensity of red-sequence galaxies in the main cluster and RXJ1347-SW.
- Comparing with simulations, the observed excess of galaxies between the main cluster and RXJ1347-SW relative to other regions around the main cluster in velocity space suggests a possible filamentary structure connecting these two clusters. This structure has a large population of blue galaxies associated with the overdensity of red-sequence galaxies, suggesting that targeting overdensities of red-sequence galaxies for spectroscopic follow-up allows the efficient selection of cluster members, while still tracing interesting structures with active star formation.

This work is a first result from our large on-going spectroscopic campaign. In future work, we will use the technique presented in this work to search and examine the properties of other structures, especially groups in the infall region, with the on-going data collecting.

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APPENDIX A: REDSHIFT COMPLETENESS, SUCCESS RATE AND EFFICIENCY

In Figure A1 and A2, we show the sampling completeness (number of galaxies targeted / number of all targets), and overall completeness, i.e. the success rate (number of galaxies with secure redshift obtained / number targeted) multiplied by the sampling completeness, for the red and blue population in the 4 pointings, respectively. Our overall completeness is about 50 per cent.

For red galaxies, in pointings "Centre" and "SW", about 90 per cent of galaxies with secure redshifts obtained turned out to be members; and in the rest of the two less dense pointings, the efficiency is ~ 60 per cent and ~ 70 per cent. For blue galaxies, the typical efficiency is about 30 per cent. (The relatively low efficiency of obtaining blue members is not surprising.)

APPENDIX B: REDSHIFT UNCERTAINTY

We possess duplicate observations for some of the objects that appear on both masks at each pointing. To determine the uncertainty on the redshift, we compare the difference in the redshifts of the same object from two observations in Figure B1. The histogram is the distribution of the difference in redshift (top axis) or rest-frame velocity (bottom axis) from repeated observations. The vertical solid line is the mean of the distribution, and vertical dashed lines indicate 1σ . It shows that the uncertainty on our redshift is $\sim 113 \text{ km s}^{-1}$ in the rest frame.

We also compare the redshifts determined from our observation with that from Cohen & Kneib (2002) for the matched objects. The distribution of the difference is shown in the left panel of Figure B2, with top axis in unit of redshift and bottom axis rest-frame velocity. In the right panel of Figure B2, the distribution of the difference in terms of the rest-frame velocity is normalized by the quadratically added uncertainties on our redshift (113 km s^{-1}) and that of Cohen & Kneib (2002) (which they assumed to be 100 km s^{-1}). This distribution is not significantly different from a standard normal distribution shown as the curve, although it is a small number statistics. This suggests that there

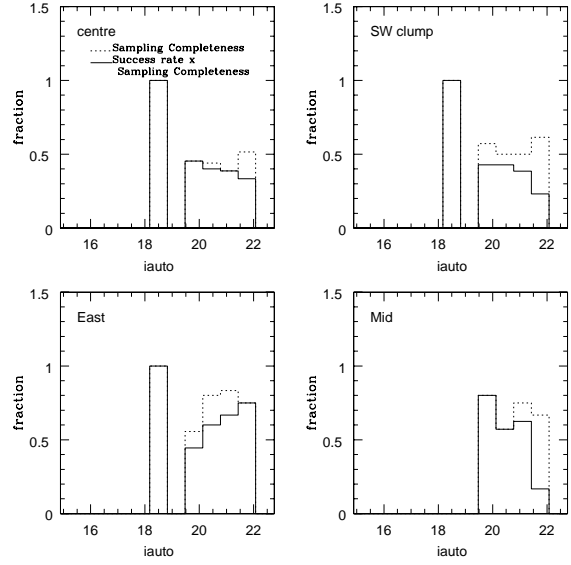


Figure A1. The completeness of spectroscopic follow-up and success rate for red galaxies in the 4 pointings. The dashed lines show the sampling completeness (number of galaxies targeted / number of all targets), and the solid lines show the overall completeness, i.e. the success rate (number of galaxies with secure redshift obtained / number targeted) multiplied by the sampling completeness.

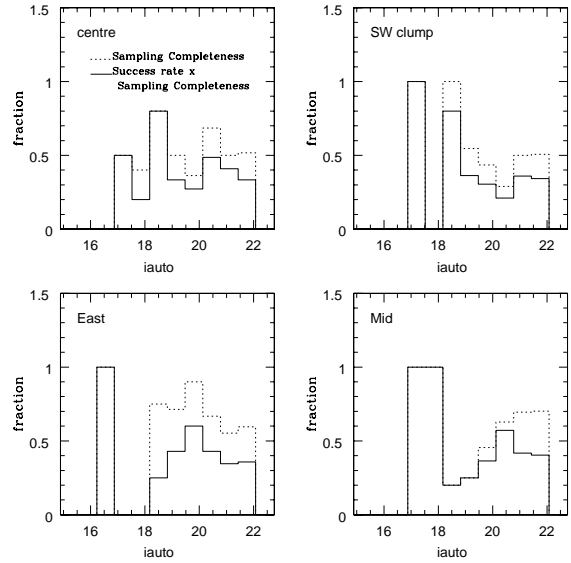


Figure A2. The same as Figure A1, but for the blue population.

is no systematic offset between the redshifts measured by Cohen & Kneib (2002) and us; therefore, we add the extra 34 redshift from Cohen & Kneib (2002) to our sample when applicable.

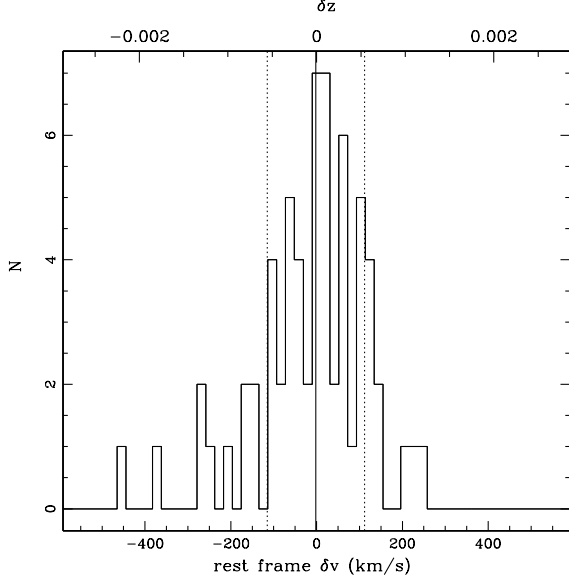


Figure B1. The distribution of the difference in redshift (top axis) or rest-frame velocity (bottom axis) for galaxies with repeated observations in our sample. The vertical solid line is the mean of the distribution, and the vertical dashed lines indicate 1σ dispersion of the distribution.

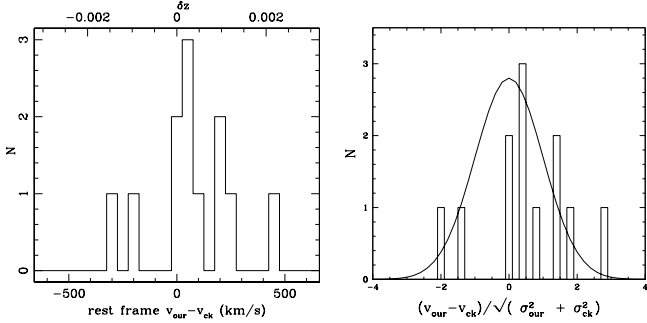


Figure B2. Left panel: the distribution of the difference in redshift (top axis) and rest-frame velocity (bottom axis) for common objects between our sample and the sample of Cohen & Kneib (2002). Right panel: the distribution of the difference in the rest-frame velocity for the common objects normalized by the quadratically added uncertainties on our redshifts and those of Cohen & Kneib (2002). The curve is a standard normal distribution.

APPENDIX C: SAMPLE SPECTRA

Figure C1 shows example spectra of two typical absorption-line galaxies with $i' = 21.4$ mag and $i' = 21.8$ mag, close to the magnitude limit of our sample. Multiple absorption features are visible, including prominent CaK, CaH, H δ , H β lines. See figure caption for description of different lines.

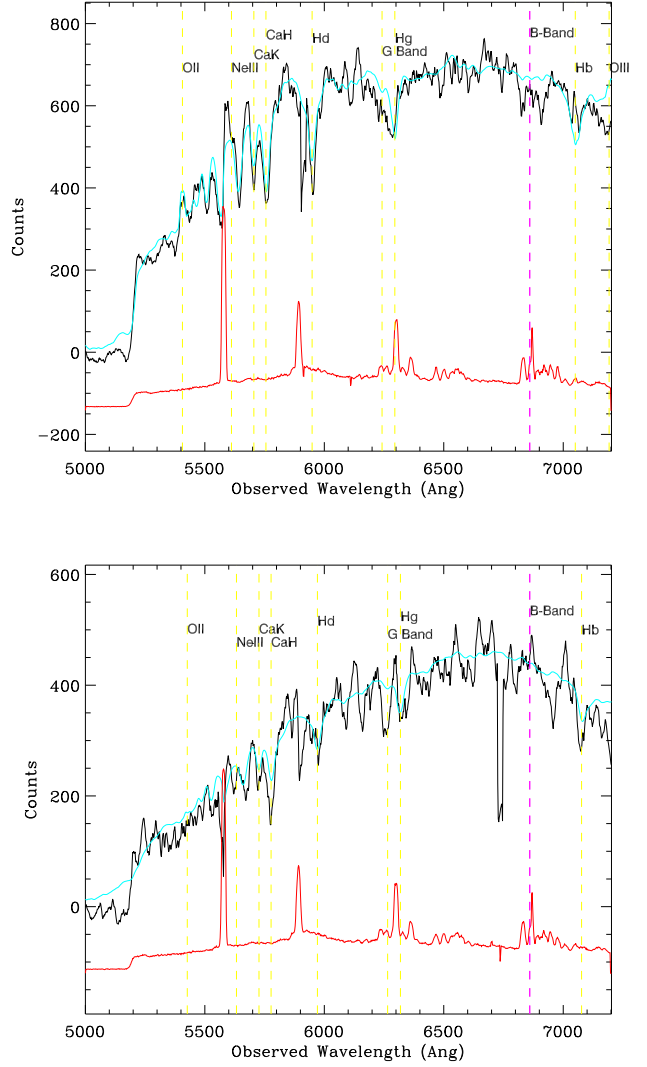


Figure C1. Example spectra (the black line) of two typical galaxies with $i' = 21.4$ mag and $i' = 21.8$ mag, close to the magnitude limit of our sample. The cyan line shows the template spectrum. The red line shows the sky spectrum, arbitrarily shifted and renormalized, to indicate where bright sky lines give rise to residuals. The positions of different spectral features are indicated with vertical lines, and in both spectra there are multiple absorption features identified, ensuring a secure redshift.